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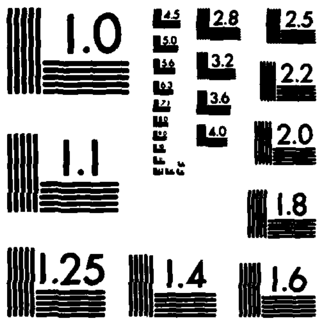

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Free Electron Lasers

AFOSR TECHNICAL FINAL REPORT - F49620-83-C-0043

Principal Investigator: W. B. Colson

1. Introduction:

Free electron lasers (FELs) amplify the radiation present in a resonant optical cavity with a co-propagating relativistic electron beam traveling along the axis of a long, undulating magnetic field. For the periodic undulator, we can describe the electron dynamics with the self-consistent pendulum equation:

$$V(z+t)=Z(z+t)=[A(z+t)\exp(iZ(z+t))+A(z+t)\exp(-iZ(z+t))]/2 \quad (1)$$

The slippage of the optical field over electrons is normalized to unity. All variables have been reduced to dimensionless form and are of order unity; their definitions are given in our previous publications. The complex optical field strength is $A(\vec{x},t)$, and the electron phase is $Z(\vec{x},t)$. The optical wave envelope is described by the parabolic wave equation:

$$(-i\nabla_{\perp}^{2}/4 + \partial/\partial t)A(\vec{x},t) = -\langle j\exp(-iZ)\rangle_{(\vec{x},t)} \quad (2)$$

where the current density is $j(\vec{x},t)$ and is the transverse gradient. We have worked out efficient numerical algorithms to solve these equations self-consistently in all four dimensions (x,y,z,t). When the electron beam and optical mode coupling is optimized, the transverse wavefront area changes significantly over the interaction length. Therefore, a theory that adequately characterizes realistic FELs will need to be self-consistent, nonlinear and contain a multimode representation of the wave in each spatial dimension. A much, more complete description is required than for a typical atomic laser where the driving medium has no structure on the scale of the optical mode.

In the past we have used our theories to solve the short pulse propagation FEL (because Stanford had a short pulse). Now we employ a similar theory to describe full multimode behavior, but with no short pulse. The trick is to calculate in a "window" with many optical field points and to use periodic boundary conditions on the electron beam.

Except for special cases, the entire multimode problem requires enormous amounts of CPU time even with the window trick. Since we know numerical computation will eventually be required for these problems, all theory is directed towards computer efficiency. In addition, we try to orchestrate all theory so that each physical effect can be encorporated into a single numerical code solving the entire FEL problem. As computing power increases, and becomes more widespread, practical application of this type or work will be fruitful. It is essential that we keep in touch with experimentalists and their specific needs. We consider the feedback essential to the development of our theory and want to direct our results to actual FEL applications.

2. Theoretical progress:

The goal of this theoretical work has been to provide a clear, intuitive description of FEL phenomena so that we have a foundation for future experiments and FEL designs. Our previous papers show how the self-consistent single-particle equations can be generalized to include the effects of collective high-gain phenomena, higher harmonics, and specialized magnet designs like the tapered undulator, the optical klystron, and the transverse gradient "gain-expansion" magnets. We continue to expand the scope of this line of thought.

Some of our 1983 effort was the documentation of earlier research in journal publications: (a) The principles of the FEL oscillator are described with new methods of analysis. The untapered FEL, tapered FEL, klystron FEL, and "gain-expansion" FEL are handled in a Physical Review paper. The complete reference is

> W.B. Colson and R.A. Freedman, "Oscillator Evolution in Free-Electron Lasers," Physical Review 27A, 1399-1413 (1983).

(b) The relevance of short and quantum noise, and a "realistic" quantum theory are developed to describe FEL start-up. The complete publication

> P. Bosco, W.B. Colson, and R.A. Freedman, "Quantum/Classical Mode Evolution in Free Electron Laser Oscillators," IEEE Journal of Quantum Electronics QE-19, 272-281 (1983).

(c) The angular and frequency spectrum for spontaneous emission in a tapered undulator were examined for the fundamental frequency and higher harmonics. The complete publication of this work is

P. Bosco and W.B. Colson, "Spontaneous Radiation from Relativistic Electrons in a Tapered Undulator," Physical Review 28A, 319-327 (1983).

(d) The development of a full multimode, non-linear, self-consistent theory for FELs was published and applied to the transverse mode behavior due to an off-axis electron beam. The final reference is

W.B. Colson and J.L. Richardson, "Multimode Theory of Free- Electron Laser Oscillators," Physical Review Letters 50, 1050-1053 (1983).

We developed a better theory for FEL longitudinal-mode studies. When electron pulses are much longer than the original Stanford experiment, CPU time becomes large and prohibitive. Unfortunately, this is the typical FEL situation. Instead of following the whole long pulse, periodic boundary conditions are used to solve the coupled equations (1) and (2) in the (z,t)-dimensions. (The theory has been presented before the JASON committee and relayed to the U. of Arizona FEL group.) As an application, we examine the synchrotron-sideband instability, and its suppression with selective mirrors. This work has resulted in two publications:

W.B. Colson and R.A. Freedman, "Synchrotron Instability for Long Pulses in Free Electron Lasers," Optics Comm. 40, 37 (1983).

R.A. Freedman and W.B. Colson, "Long Pulse and Sideband Instability in Free Electron Laser Oscillators," Bendor Island FEL Conf., J. de Physique 44, C1-369 (1983).

In an invited paper at the Bendor Island FEL Conference, A. Renieri and I reviewed the work of several research groups on the topic of FEL short pulse propagation: theory and experiment. The extensive work on this subject was stimulated by the early Stanford experiments whose results necessitated the inclusion of the "lethargy" effects. The general conclusion is that theory and experiment are in good agreement; the remaining differences are difficult to pursue in detail further because of inherent uncertainties in the experiment. For instance, the alarm of "slow FEL start-up" was resolved when it was found that due to accelerator-klystron- cavity "loading", the Stanford electron beam did not have a stable energy. The review paper also suggests future applications for the theoretical approach. The reference is

W.B. Colson and A. Renieri, "Pulse Propagation in Free Electron Lasers," Bendor Island FEL Conf., J. de Physique 44, C1-11 (1983).

In collaboration with LANL, we examined the effect of energy spread and emittance on the growth of the synchrotron-sideband instability. For the LANL parameters, there was some reduction in the growth rate, but instability was still quite prominent. Generally speaking, any procedure used to eliminate the instability also leads to less power since the increased power is always in sidebands. The simplest means of removing the sidebands seems to be decreasing the electron beam current or resonator Q. This work was reported in

J.C. Goldstein, W.B. Colson, and R.W. Warren, "Tapered Wiggler Free Electron Lasers Driven by Non-Monoenergetic Electron Beams," Bendor Island FEL Conf., J. de Physique

44, C1-371 (1983).

J.C. Goldstein and W.B. Colson, "Control of Optical Pulse Modulation Due to the Sideband Instability in Free Electron Lasers," Proceedings of the 1982 International Conf. on LASERS, New Orleans, LA (Dec. 13-17, 1982).

Further support of the LANL experiment and the strong-field synchrotron instability has used the periodic window for optical mode analysis. Using the LANL parameters current and magnetic field strength, the effect of the resonator on mode stability was examined. It was found that as much as 20% loss/pass was necessary for the FEL to run without sidebands. When the losses were dropped to 14% pass, a single sideband appeared in the untapered FEL planned at LANL. When the losses were lowered to 1% (as eventually planned), the optical field became chaotic and the FEL went broad band.

With 5% taper in the undulator wavelength, the sidebands did not appear until loss was about 7%. Arguments are given as to why the tapered FEL is less sensitive to the instability. However, at the planned 1% loss the tapered FEL fields also became chaotic and broadband.

Another lesson was learned from this work as well: tapered FELs do not function as tapered FELs in high Q resonators. By this I mean that the resonator Q is a more effective means of extracting electron beam energy than tapering. This conclusion should alter the way future FEL are designed; there appears to be little need to ever taper. This work has been prepared and will be reported in

W.B. Colson, "1983 Free-Electron Laser Workshop" Free

Electron Generators of Coherent Radiation, SPIE Vol. 453, xx (1983).

In collaboration with I. Boscolo (who was visiting UCSB this year), we improved the description of high-gain klystron- FELs. Previous authors have assumed low-gain in the analysis of the high-gain klystron, and we numerically calculate the correct gain self-consistently. The result is a new gain curve for the klystron with absorption peaks much smaller in amplitude than gain peaks. As a result true high-gain klystron may be less susceptible to electron beam energy spread and emittance than predicted by previous theories. A manuscript has been prepared and is to be submitted to Physical Review A.

One of our tasks this year was to explore new ways of obtaining the computing power. There appeared to be the possibility of buying, or building, an expensive array processor to specifically solve FEL problems. After much discussion with local and non-local experts we found that the kind of array processor we needed cost about $150 K to $200 K. This put us in the price range of commercially available array processors. (The same conclusion was reached for another similar project here on campus.) We then collected literature and information about the VAX 11/780, Star ST-100, IBM 3838, CSPI MAP-400, and the FPS 120 B. The prices range from $120 K to $750 K, and the performance is from 0.01 to 0.5 that of a CRAY. A crucial problem with such a purchase is the maintenance of this kind of equipment; departmental technical support on the UCSB campus is small and subject to change.

A much better solution for the next year is to request CRAY computing time (or equivalent) from AFOSR. This is provided now through AFWL. The computers we have been using on campus have become very busy while our computational needs have increased. We want to use an IBM PC as a workstation for developing programs and analyzing results from the CRAY. Some supporting software is requested through this proposal.

We have started what we hope is a long-term collaboration with the Frascati-Microtron-FEL group. A good relationship with them is attractive to use for three major reasons: (1) They are working on small, flexible FELs and now use microtrons for this purpose. This kind of FEL provides good feedback to a simulation group like ours because they can do experiments quickly and modifications are easy. (2) The theory group in Frascati is one of the strongest and has a good classical and quantum picture of the FEL. We have arranged to work with them to direct their formalism toward more practical applications and incorporate their quantum statistical work into our computer simulations. This is important for short wavelength FELs. (3) The personnel in our two groups seems to have an excellent, productive working relationship.

The Frascati group has provided funds for the exchange of people in the next few years. They want help with theoretical support and we get experimental data; also, experiments are being designed to specifically test our theories.

In this year Frascati-collaboration we worked out a theory and an estimate of the gain available off-axis in higher harmonics of an FEL. The FEL is unique because the output wavelength can be tuned over wide ranges by merely misaligning the undulator, electron beam, and resonator axes. The intentional this has practical applications, and even unintentional, the resulting characteristics must be understood. For instance, an electron beam with some emittance (and therefore an angular spread) will have non-zero gain in all higher harmonics; previously it has always been said to be zero gain. The new gain is caused by the off-axis electrons. A manuscript co-authored by G. Dattoli will be submitted to Physical Review A.

In our continued effort to maintain a close connection, to FEL experiments, we have directly supported TRW and LANL in the design of their systems. We made computer runs this year with the proposed parameters of the TRW/Stanford FEL in order to predict the start-up time, estimate transverse mode effects, and the results of the synchrotron-sideband instability. We try to give the experimenter some "simulation experience" before he actually runs the FEL. When real data comes in and is "disguised" by reality, it is helpful to have some experience for interpretation and diagnostics of problems. In the future of FELs, these expensive experiments will need extensive computer simulations for the analysis of results and the design of new experiments. The connection to TRW/Stanford, LANL, and Frascati is now close, and we intend to extend this relationship to Lawrence Livermore Lab as well in the near future.

Throughout these studies, graphical representations of optical mode evolution and electron phase-space evolution has been helpful in understanding FEL physics. The graphs not only help in the research, but make communication of our results much easier. Figure 1 is an example of some of the capability. We can now make computer generated color movies, color slides, color prints, prints with 32 grey scales of publication quality.